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ENHANCING THE CONSTRUCTION SAFETY TRAINING BY USING VIRTUAL ENVIRONMENT: V-SAFE

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Abstract: Construction is one of the most high-risk industries in the world. The safety records of the construction sector report that, construction workers are approximately over three times more likely to be exposed to serious accidents comparing to other industries. In addition to these injuries and fatalities, work-related accidents also cause financial damage, conflictual cases and pecuniary penalties for the construction companies. Therefore, the significance of the safety management process has been increasing in the construction industry. However, since the majority of the construction activities are complex and require collaboration between the workers, the provision of the safety has become one of the challenging tasks. So, the behavior-based skills of the workers play a crucial role in the safety management. Traditional safety training methods have been merely focusing on information-based techniques such as lectures, videos, written materials, etc. On the other hand, previous research has indicated that adequate safety training should also involve behavioral modeling and hands-on training, together with traditional learning methods. Due to the nature of the construction projects, hands-on training in the construction field is not practicable. In this sense, using virtual environments is an effective method that enables a safe environment for the users without being exposed to adverse effects of the failed tasks. Thus, virtual environments allow visual simulation that is helpful for the improvement of the trainees' behavior-based skills. Therefore, virtual environments provide an important opportunity to advance the level of safety training. The main aim of the study is to describe the developed virtual safety training environment called V-SAFE (Virtual Safety Analysis For Engineering applications), which involves methods to simulate, and visualize construction operation scenarios. V-SAFE is based on the Unreal game engine for the visualization of the environment, and USARSim is used for the high-fidelity simulation of the robot behavior and environment mapping. V-SAFE is projected to establish a base to identify construction-specific safety risks and to improve the behavior-based skills of the construction project participants. In brief, V-SAFE has high potential to improve the risk recognition capability, and situational awareness of the construction managers, workers, safety managers, field engineers. So, V-SAFE could be beneficial for the construction organizations aim to advance the effectiveness of the safety training.

1 INTRODUCTION

The number of fatal accidents in the construction industry indicates the risky environment of the construction projects. During a 10 year period between 2004 and 2013, 558 fatal accidents were recorded in Canadian construction industry which was accounted for the highest number of fatal occupational accidents of any industry sector (Workplace Safety and Insurance Board, 2013). Quite similarly in the United States, around 800 occupational fatal accidents occurred in the construction industry that correspond to 11.8 per 100,000 full-time equivalent workers in 2013 (U.S. Bureau of Labor, 2014). Moreover, the fatality rates did not differ in the European Union (EU) countries. Approximately 3,800 fatal injuries occurred in 27 European countries in 2012 (Eurostat, 2013). Shortly, statistical results demonstrate that construction workers are exposed to excessive on-site hazards that could result in injury or even death. Therefore, we can conclude that occupational accidents in the construction industry are still a major worldwide problem.

The occupational accident records clearly indicate inadequacies in the construction safety management process (Waehrer et al., 2007). Coleman (1991) highlights that about 90% of the fatal construction hazards could be avoided and 70% of these construction site accidents origins from the inadequate safety management action. Similarly, Carter and Smith (2006) also show that hazard identification level in the construction projects are not satisfactory, and 33% of the risks could not be precisely identified by the workers. As a result of the insufficient hazard identification level in the construction field, accidents inevitably occur on the construction site. One of the main reasons of the unforeseen hazards could be the lack of adequate safety training for the workers in the construction industry (Helen and Rowlinson, 2005). Several studies thus far have highlighted that efficient safety training could improve the hazard identification and with this way the accidents could be prevented before they occur.

Moreover, previous studies (Hung et al., 2013; Aranda, 2000) have shown that, traditional training methods might be able to improve the hazard identification level only to some extent that is not sufficient. For instance, Hung et al. (2013) found that fall-protection training could be able to improve the identification of some risk sources leading to the falls. Similarly, Aranda (2000) utilized the navigable movies to set-up training program for the improvement of the hazard identification. However, all of these training methods merely focus on the information transfer by using the materials such as lectures, 2D drawings, photos, etc. Yet, previous research has indicated that adequate safety training should also involve behavioral modeling and hands-on training, together with traditional learning methods (Burke et al., 2006), but, the application of the highly engaging training in the construction field is not practical, it is costly and even risky. Considering the need for an alternative safety training method, this paper introduces a novel method using virtual reality that involves both behavioral modeling and hands-on training in a risk-free environment.

2 LITERATURE REVIEW

The provision of the adequate safety training is one of the challenging tasks in the construction industry. Therefore, in order to provide an effective safety training, identifying the critical issues for the improvement of the safety training is important. Frese and Zapf (1994) state that, proactive training methods are more efficient, comparing to passive techniques. In other words, Frese and Zapf (1994) argue that conveying the safety information by practice plays a crucial part in the effectiveness of the training. Similarly, Burke et al. (2006) extended the measurement of safety efficiency approach by categorizing the training methods. Accordingly, Burke and colleagues identify three main safety training methods; least engaging, moderately engaging and highly engaging (Burke et al., 2006). The least engaging training methods are the information delivery systems such as videos, written information, lectures, etc. The major limitation of the least engaging methods could be considered as only focusing on the information delivery, rather than practical training. On the other hand, moderately engaging methods also consist of quantitative feedback-based training methods such as questionnaires, interviews, etc. Comparing with the least engaging methods, moderately engaging training methods also provide feedback to the users. Finally, according to Burke et al. (2006) the most engaging active training methods should cover the integration of the knowledge transfer and behavioral modeling. So, a precise safety training should involve relevant information transfer, hands-on training, behavioral modeling, and feedback mechanism (Burke et al., 2006). However, due to the nature of the construction projects, hands-on training in the construction field is not practicable; it even increases the risk of accident.

In this sense, using virtual reality based training tools could be a suitable method for the trainees since virtual training provides a safe work space for the users without being exposed to negative effects of the failed tasks. Consistently, Sokolowski and Banks (2009) also state that the use of virtual simulation is useful when it is not possible to interrelate with the real system. So, the virtual system could be helpful to the users to apply the training recursively. Thus, they could learn from their mistakes and correct them. As a result, users could enhance their safety knowledge by modifying their safety attitudes and improving their cognitive abilities.

Similarly, virtual reality-based training systems have been used in several fields. Preliminary work on surgeon simulation was undertaken by Satava and Fried (2002) to describe the effects of using the virtual reality to advance the surgical simulation performance by the improvement of the relevant psychomotor skills. On their comparative experiment, results show that the use of the virtual training significantly improved the operation performance of the surgeons. Consistently, Lin et al. (2007) assessed the cognition capabilities of the drivers by quantifying the responses. The study shows that adequate virtual training could significantly improve the drivers' cognitive responses.

Similarly, virtual environments have been used in various fields in the construction industry as well, such as information management, geotechnical engineering, scheduling, structural design, etc. For instance, Arduino et al. (1997) developed an innovative virtual reality-based training platform for the trainees by using a geotechnical triaxial device. Study results show that virtual reality based training was helpful for the users to understand the soil behavior. In addition, a comparative study of Comu et al. (2011) measures the impact of the facilitation in a global project while the participants are geographically distant. Accordingly, results provide an insight into the role of the facilitation in the virtual project networks. Similarly, Wen et al. (2009) used the virtual reality for the training of the rigging operators. Results show that the trainees' operating skills were positively affected by the use of the virtual training.

The studies presented in different fields of the construction area point out that virtual reality has a great potential to improve the training level. Recent and growing body of literature has investigated the use of the virtual safety training tools in the construction industry. In a comparative analysis, Albert et al. (2014) aimed to improve the hazard recognition skills of the workers by using the virtual reality based safety training tool. As a result, a human-computer interactive augmented virtuality training platform was developed and cognitive mnemonics based on energy sources such as mechanical, electrical, etc. were presented. The results show that identifying hazards according to the energy-based cognitive mnemonics significantly improves the hazard identification level by the support of the systematic categorization. Similarly, a recent study by Guo et al. (2012) integrated serious gaming technologies into the construction safety management process to improve the training performance. The study reveals that the safety performance of the plant operatives and tower crane workers were significantly improved. Quite similarly, Le et al. (2014) developed a safety training tool for the safety education purposes. The system provides a role-playing platform for allowing the students for dialogic and experiential learning. Moreover, Park and Kim (2013) created a framework for the visualization of the novel safety management process by integrating building information modeling, location tracking, and augmented reality. Study results show that safety management visualization systems improve the hazard identification and the real-time communication between construction management team and workers. Taken together, these results indicate that the virtual safety training tools and visualization system improve the construction safety management by enhancing the effectiveness of the field safety risk identification, providing a better understanding for the workers about risk recognition, improving the real-time communication between construction manager and workers.

In the lights of these several studies (Albert et al., 2014; Guo et al., 2012; Le et al., 2014, Park and Kim, 2013) which contribute to the body of literature of construction safety management, we also aim to make a meaningful contribution. In this study, we analyzed the features, characteristics, and potential contributions of a virtual platform called V-SAFE (**V**irtual **S**afety **A**nalysis **F**or **E**ngineering applications). In addition, the paper also discusses how the V-SAFE could be able to address the inadequacies in the construction safety training in a systematic manner by offering an enhanced and highly engaging training method. Hence, the study provides insights in a way that how virtual safety training could be applied in construction-specific training program. In addition, the study highlights that features of the virtual tools play an important role in the construction safety training.

3 RESEARCH METHODOLOGY

3.1 Overview of the Virtual Safety Analysis For Engineering applications (V-SAFE) Development

The main objective of this study is to develop a virtual reality based safety training tool for the construction industry. The tool simulates hypothetical construction activities in a three-dimensional (3D) virtual media. The main properties of the tool such as surrounding environment, reality integration, and collision detection, help to improve the hazard identification level of the users, and also advance their behavior-based skills. In other words, by using the V-SAFE, the trainees are exposed to real construction risks in a virtual simulation environment. Accordingly, users learn about the hazards they may face in their workplace and experience the potential consequences of their own mistakes or their colleagues' mistakes, in a safe virtual environment. In addition, this software also aims to enhance the performance of the operators since it provides repeatable training practice. In the virtual environment, workers are subjected to varied alternative incidents in putting up a brick wall. In this task, we defined two different roles as the crane operator and site workers that are assigned on-site duties. The task-based simulation consists of the major factors leading to hazards in the field, and trainees are asked to finish their task with appropriate safety behavior. Thus, the system aims to not only improving the hazard identification level of the workers, but also, enhancing the collaboration between different participants in the field.

V-SAFE is based on the utilization of the "Unreal Engine" by virtue of the "Unreal Software Development Kit". Unreal Engine (UE) is a cross-platform game engine written in C++ first released in 1998 by Epic Games, which is a popular game engine. The usage of the Unreal Game Engine is not limited to the games. NASA, U.S. Department of Transportation and Warner Bros are listed among the licensees of UE3 (Slashdot, 2006; Epic Games, 2011).Consequently, UE3 is also used in training, transportation and movie storyboard simulations.

Another component of the V-SAFE is USARSim (Unified System for Automation and Robot Simulation). USARSim is a robot simulation environment built using UE3. USAR enables combining the use of engineering and scientific application in the adequate virtual environment (Balakirsky et al., 2006). Recently, researchers have shown an increased interest in the use of USARSim, due to its broad range of expertise such as advanced locomotion systems, sensor fusion, cooperative multi-agent planning, human-robot interfaces and more. USARSim, an open-source project is funded by National Science Foundation, supervised by National Institute of Standards and Technology and used in rescue virtual robot competition league of RoboCup (Balakirsky et al., 2006). USARSim is designed to simulate disaster scenarios in which virtual robots perform rescue missions (Balakirsky et al., 2006). For this purpose, many robots and sensors are implemented in UE3. In the V-SAFE, USARSim is used to control autonomous agents in the simulation environments and observe the environment using sensors.

The general structure of the V-SAFE involves four major stages. In the first phase, users create their accounts and avatars. Hence, they could share their personal information through the media with the other users. Secondly, users select their simulation preferences using the Lobby Web Server interface via their web browsers. Thirdly, when all users are ready, the web browser starts the USARSim and Unreal Simulator with the given parameters. Finally, during the simulation, the USARSim, and Unreal Simulator communicate with the simulation coordinator running on the V-SAFE server. Simulation Coordinator tracks the state of the simulation on all users' accounts and synchronizes the simulation events when necessary. The structure of the V-SAFE training system that involves the data tracking and visualization is shown in Fig. 1.

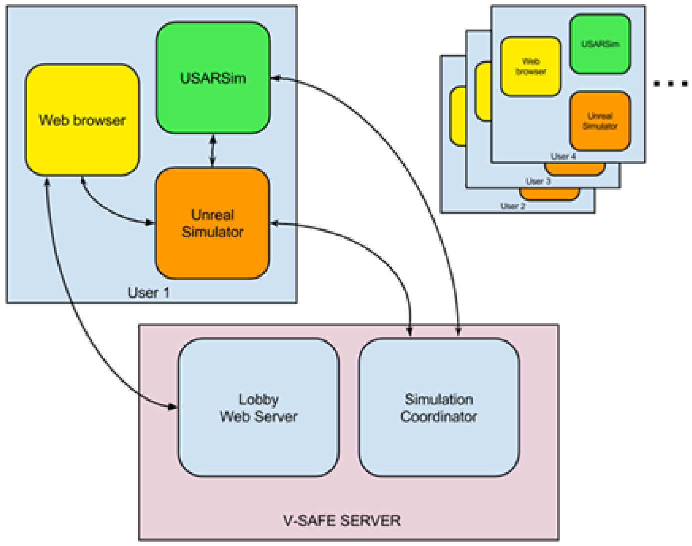

Figure 1 Workflow of the V-SAFE Training System

As we mentioned, the V-SAFE is powered by Unreal Game Engine and Unreal Software Development Kit. So, all the components, functions, and digital tools were all developed through the Unreal Development Kit and USARSim editors and the kits in the game engine. First of all, terrain editor function primarily aims the integration of the virtual terrain to the virtual scene (Mooney, 2012). The general virtual terrains are supported by the dynamic multiple layers of the deformable blended materials. Thus, virtual terrains such as grass, concrete, etc. could have been integrated into the virtual environment. Secondly, object modeling is also another important feature of the environment. In our study, we defined static and dynamic 3D objects related to the construction tasks such as the crane, building, electrical equipment, scaffold, machinery, etc. In the modeling process, object editor provided to input the geometric properties of the materials inside the virtual environment, accordingly the quality of the simulation is significantly enhanced. The third important feature of the engine is the collision detection system. This feature allows the users to move around and inspect the elements of the virtual environment. So, collision detection development advances the realistic effects of the virtual media (Mooney, 2012). By using these functions, all the simulation related elements were embedded into the virtual environment.

3.2 V-SAFE Training Procedure

The training procedure of the V-SAFE was based on three steps. In the first step, we identified all the possible hazards that could have occurred during the building up a brick wall task based on previous construction projects. In addition, we also considered the number of the identified hazards; precursors lead to these hazards, and their potential impacts. In other words, we defined which accidents are more likely to occur, how these hazards could be prevented and what are the possible effects of these hazards. By this systematic analysis of the hazards, we identified the most critical hazards for the simulated construction activities. In the second part, we defined these hazards into the virtual environment of the V-SAFE together with their probability of occurrence. During the identification of these hazards, we assigned three principal reasons of the hazard occurrence as material-based, safety knowledge-based and behavior-based. Thirdly, we associated these hazards with the objects and activities in the virtual environment. After the completion of three stages, we developed the main scenario. Thus, we finalized the V-SAFE virtual environment for the user interaction.

After the completion of the V-SAFE virtual environment, we conducted an alpha test in order to validate the functionality of the V-SAFE. The Alpha test was aimed to gather information about the strengths and limitations of the V-SAFE and to evaluate the fundamental functions of the virtual tool. So, the preliminary analysis of the V-SAFE could be conducted, and the tool could be upgraded considering the feedback provided by the trainees. During the preliminary analysis, firstly the trainees were assigned two different roles that are the crane operator and the site worker. For instance, when building up a brick wall, the crane operator moves the necessary materials and equipment to the designated work area on the second floor. In the virtual environment, even though users attempt to fulfill their assigned duties individually, at the same time they closely collaborate in the environment. According to their behavior in the virtual environment, trainees could be possibly become subjected to different types of exposures such as falls, struck by the objects, electric shock, etc. Consequently, during the alpha testing, participants were asked to monitor and use the V-SAFE environment and models to evaluate the system competence for the user interaction.

During the interaction, trainees use the standard computer hardware such as keyboard, mouse and monitor. The viewpoint is based on the first person view of the avatar, and the users could move their avatar by using the keyboard and mouse (Fig. 2.).

Figure 2 The view of the virtual environment based on First-Person Point of View

Mouse provides the orientation of the character in z-axis while the keyboard provides the movement in x and y axes. During the virtual tour, the users could walk on the virtual terrain and interact with the static and dynamic 3D objects and other users by their avatars (Fig. 3.). So, the users can interactively take place within the simulation, and they can repeat the virtual training till the desired performance level is achieved.

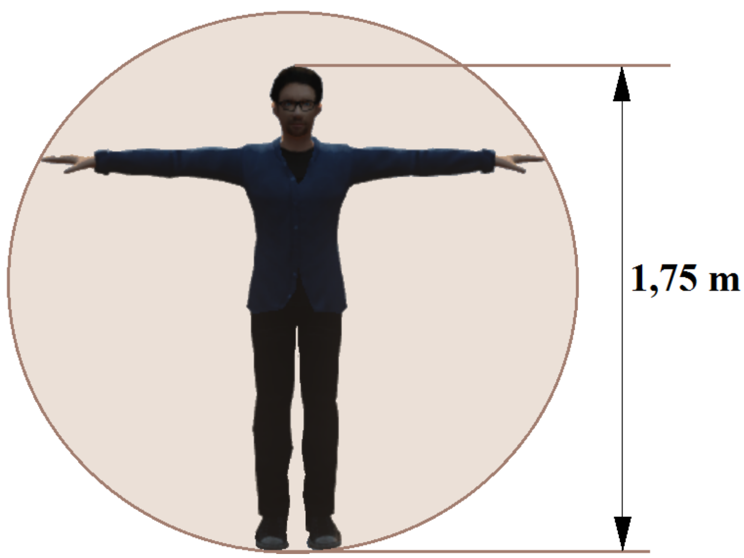

Figure 3 Graphical model for the human body (Avatar)

4 DISCUSSION

In this research, we aimed to develop a highly engaging safety training tool, the V-SAFE, which involves necessary information transfer, hands-on training, behavioral modeling, and feedback mechanism. As mentioned in the literature, there are potential benefits of using the virtual reality based construction safety training tools. In traditional hazard identification, the identification process is satisfied with the examination of the 2D materials such as drawings, structural and architectural designs, photographs and videos. However, this approach does not improve the spatial awareness and decision-making capabilities of the trainees. As a result, the cognition and vision of the users are extremely limited, and several potential hazard sources could be easily neglected, due to the lack of the third dimension consideration. However, the virtual environment could improve the spatial awareness by establishing a base for manipulating with the objects and navigating in the virtual environment. Thus, the hazards could be identified more effectively since 3D environment supports the correct safety information processing and enables collaboration among the users.

All previous studies (Albert et al., 2014; Le et al., 2014; Park and Kim, 2013) show that virtual construction safety training methods improve the hazard identification level, even though the methods used vary significantly. For example, Park and Kim (2013) aimed to integrate a question and answer procedure into the relevant hazard sources. Thus, the related safety questions about the risk sources could be directed to the trainees while the users encounter with the hazard source in the virtual environment. In that case, the virtual environment could be considered as a moderately engaging training method according the definition by Burke et al. (2006), since this technique focused only on the transfer and evaluation of the safety information. On the other hand, this method did not address behavioral modeling and safety attitudes of the users. Similarly, Le et al. (2014) developed a safety training tool based on the inspection of the virtual media. During the investigation of the different construction tasks, users can monitor potential hazards in the custom scenarios. However, this method still fails to evaluate the users' safety behavior. In the same vein, Albert et al. (2014) developed a human-computer interactive augmented virtuality and cognitive mnemonics based on construction hazards and on-site energy sources. With this approach, the safety memories of the users were significantly improved, yet the study was not aimed to improve the behavioral safety approach. So, the common characteristic of all of these existing approaches could be considered as the usage of virtual training tools as the enhancement of the traditional methods while they are still at the moderately engaging level.

With the V-SAFE, we aimed to fill this gap in the literature by developing a tool that provides highly engaging safety training unique to the construction industry. First of all, we formed up an experiential learning method, for not only improving the hazard identification level, but also improving the users' behavior-based safety skills at the same time. The term experiential learning refers to the process of learning directly from the experience (Gentry, 1990). However, processing the safety information through experience on the construction sites is not practical. In this sense, the V-SAFE tool provides a safe platform for hands-on training. With this way, users could accumulate their safety knowledge and improve their behavior. During the alpha test, each trainee was given a different role in the simulation. For instance, one of the users was responsible for the crane operation, which requires both the use of safety information and correct decision-making process. As a result of this interaction between the users and the surrounding virtual media, trainees oriented to improve their safety behavior and gain practical experience.

Another significant feature of the virtual construction safety training is the provision of the individual and interpersonal learning (Wen et al., 2009). In the learning process, self-learning is an important part of the safety training especially for the workers with insufficient safety knowledge. In the construction projects, falls are among the most common causes of occupational accidents. For instance, during the virtual training, the inadequate behavior of a user such as not wearing a full-body harness could lead to the falls. By realizing the consequence of such an action in the virtual environment, users could modify their safety behavior in the real workplace. As a result, trainees could learn about the construction hazards in the virtual environment and do not repeat the same hazardous actions on job-site. Just like self-learning, interpersonal learning is also another major part of the virtual safety training (Wen et al., 2009). The V-SAFE establishes a platform for the trainees that interact with other users and with this way learn from each other. For instance, when a user violates a safety rule in the virtual environment, other users could warn him to modify his action. Similarly, trainees can also observe the safety violations and take lessons from others' mistakes. Therefore, utilizing the V-SAFE has a great potential to fulfill two primary learning models by providing collaborative tasks and multiuser environment.

One of the most important features of the simulated environments is providing the sense of reality (Park and Kim, 2013; Albert et al., 2014; Cheng and Teizer, 2013). In other words, the users interact with the surrounding environment and other participants as it is in a real workplace. In the virtual environments, the sense of reality is also supported by spatial awareness of the users. Accordingly, by interacting with the 3D environment, the users can improve their hazard identification understanding. In order to provide a better hazard identification process, the sense of reality and the visualization quality of the virtual tool are extremely significant. In this sense, visual features, object modeling, etc. of the virtual environment should be realistic and visually effective. In the V-SAFE tool, UE3 supports several image quality functions such as rendering, auto adjusting, etc., which provides high-quality images and object modeling. As a result, users could be able to monitor the virtual environment and the objects in the high quality and full HD resolution. Briefly, more effective visualization by the V-SAFE has a high potential to improve the sense of reality and spatial awareness of the users.

This study demonstrates the features and potential benefits of the V-SAFE training tool based on the alpha test results. The results of the alpha test show that the main functions of the tool such as collision detection, terrain generation, static and dynamic models run without having a major problem. Moreover, we noticed that the multiuser environment of the V-SAFE successfully enabled both the user-to-user and the user-to-virtual object interaction. On the other hand, there are several limitations in this study. First of all, because the V-SAFE is at the alpha testing stage, the number of the scenarios, objects and assigned roles to the trainees were considerably limited. As mentioned, we defined only two major roles that are the crane operator and site workers. Also a single construction scenario, building up a brick wall on the second floor, was implemented. At this stage of our research, we only focused on developing the V-SAFE and identifying the work logic, methods and training procedure. In the following versions of the tool, we plan to simulate more construction process tasks among more roles. Consequently, we will conduct a pilot test of an upgraded version of the V-SAFE. Hence, we will be able to evaluate the training effectiveness of the V-SAFE more accurately.

5 CONCLUSION

The safety management of construction projects is extremely challenging due to projects' dynamic and complex nature. Providing adequate training could be considered as an important element of the safety management process. Traditional safety training methods have been merely focused on information transfer techniques. The recent developed virtual safety training tools convey the safety information through a 3D supported environment that improves the hazard identification level of the users. Yet, the safety behavior of the users has not been taken into account. This study fills an important gap in the literature by recommending a highly engaging training method for the construction projects. In this study, we introduce the V-SAFE that is a virtual reality based safety training tool and also evaluate the potential benefits of using it in order to achieve a better safety performance level. We also showed that this tool can improve the risk recognition capability and the spatial awareness of the users. Consequently, the V-SAFE contributes not only to the literature on construction management but this novel method could be beneficial for the construction organizations that aim to advance the effectiveness of the safety training and hazard identification level.

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